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 Consumer Electronics, IEEE Transactions on , Volume: 46 , Issue: 3 , Aug. 20  
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[\[Abstract\]](#)   [\[PDF Full-Text \(472 KB\)\]](#)   IEEE JNL

### 2 Adaptive timing synchronisation scheme for short-range Bluetooth network

Young-Hwan You; Min-Chul Ju; Cheol-Hee Park; Jong-Ho Paik; Hyoung-Kyu S  
 Electronics Letters , Volume: 36 , Issue: 9 , 27 April 2000  
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### 3 Performance of simple timing synchronization and DC-offset compensation schemes for a short-ranged Bluetooth network

Young-Hwan You; Cheol-Hee Park; Min-Chul Ju; Jong-Ho Paik; Jin-Woong Cho  
 Hyoung-Kyu Song;  
 Personal, Indoor and Mobile Radio Communications, 2000. PIMRC 2000. The 1  
 IEEE International Symposium on , Volume: 2 , 18-21 Sept. 2000  
 Pages:1320 - 1324 vol.2

[\[Abstract\]](#)   [\[PDF Full-Text \(460 KB\)\]](#)   IEEE CNF

### 4 Adaptive timing synchronization scheme for a short-ranged Bluetooth network

Young-Hwan You; Min-Chul Ju; Cheol-Hee Park; Jong-Ho Paik; Hyoung-Kyu S  
 Consumer Electronics, 2000. ICCE. 2000 Digest of Technical Papers. Internati

Conference on , 13-15 June 2000  
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Merchant, A.; Yu, P.S.;

Computers, IEEE Transactions on , Volume: 44 , Issue: 3 , March 1995

Pages:419 - 433

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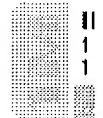
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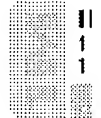
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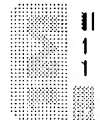
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*Wei-Bo Gong; Nananukul, S.; Yan, A.;*

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Computers in Cardiology 1996 , 8-11 Sept. 1996

Pages:85 - 88

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**10 Altered cardiorespiratory control in patients with severe congestive heart failure: a transfer function analysis approach***Sobh, J.F.; Lucas, C.; Stevenson, L.W.; Saul, J.P.;*

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*Yingthawomsuk, T.; Kawada, T.; Sato, T.; Inagaki, M.; Sunagawa, K.; Cox, J. Shiavi, R.G.; Diedrich, A.;*

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*Barbieri, R.; Di Virgilio, V.; Triedman, J.K.; Bianchi, A.M.; Cerutti, S.; Saul, J.* Engineering in Medicine and Biology Society, 1995. IEEE 17th Annual

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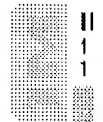
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## ADAPTIVE TIMING SYNCHRONIZATION SCHEMES FOR A SHORT-RANGED BLUETOOTH SYSTEM

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### ABSTRACT

*This paper describes two adaptive timing synchronization schemes for a short-ranged Bluetooth system in the partial-band noise environments. One estimates the variance of the partial-band interference, which is utilized for the trigger threshold value of the inquiry scan and page scan states, while second is designed using the scaled partial correlation value for the connection state. Numerical results show the proposed synchronization algorithms are robust to the partial-band noise interference and of low complexity, which is suitable for a low-cost personal area network (PAN).*

### 1. INTRODUCTION

Recently, much attention have been brought to a new class of home- and personal-area network (PAN) devices with low-cost technologies such as HomeRF, HomeCast, and Bluetooth [1][2]. Especially, Bluetooth is focused on a low-cost short-range radio link, facilitating protected ad-hoc connections for stationary and mobile communication environments as shown in Fig. 1.

Bluetooth transceiver operates in the unlicensed 2.4 GHz ISM band. Cordless phones, garage door opener, microwave ovens, and other PAN devices such as HomeRF and IEEE 802.11 also operate in this band and among these devices microwave ovens are the strongest source of interference. In the Bluetooth system, using a frequency-hop (FH) technique and error correction algorithms, the interference protection can be achieved [1]. However, the interferences from other PAN devices operated in the ISM band will prevent Bluetooth units from establishing reliable synchronizations and connections.

This paper is concerned with two adaptive timing synchronization schemes in the frequency-hopped Bluetooth system. The performance of the synchronization receivers is examined in the presence of the partial-band noise jamming in terms of the detection probability. In this paper, we consider the partial-band interference, which may be due to a partial-

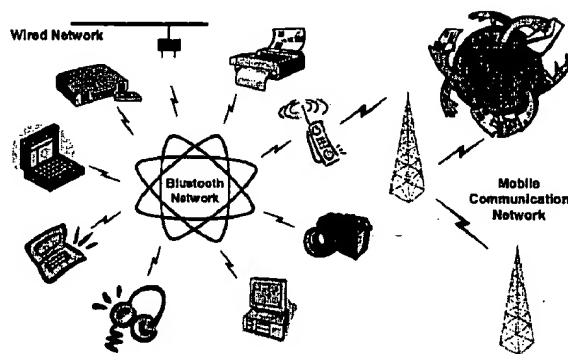


Fig. 1. Bluetooth network

band jammer as well as other unwanted narrowband interferences, and is modeled as additive Gaussian noise [3][4]. Furthermore, the interference is assumed to be present in a frequency shift keying (FSK) demodulator for any reception of the dehopped signal with probability  $r$ . The proposed timing synchronization techniques are robust to the partial-band noise interference and have a good estimation accuracy with a low complexity.

The outline of the paper is organized as follows. Section 2 describes the Bluetooth system model and the connection process. In Section 3 and 4, the proposed timing synchronization algorithms and their performance are presented in detail, respectively. Some numerical results are presented in Section 5. Finally, the concluding remarks are given in Section 6.

### 2. BLUETOOTH SYSTEM

#### 2.1 Overview of Bluetooth system

Bluetooth uses a slotted time-division duplex (TDD) scheme for full-duplex transmission, where each slot is 0.625 ms long (two slots form one frame) and a Gaussian-shaped FSK (GFSK) modulation is applied to minimize transceiver com-

- master unit perform inquiry or page scan to make connection

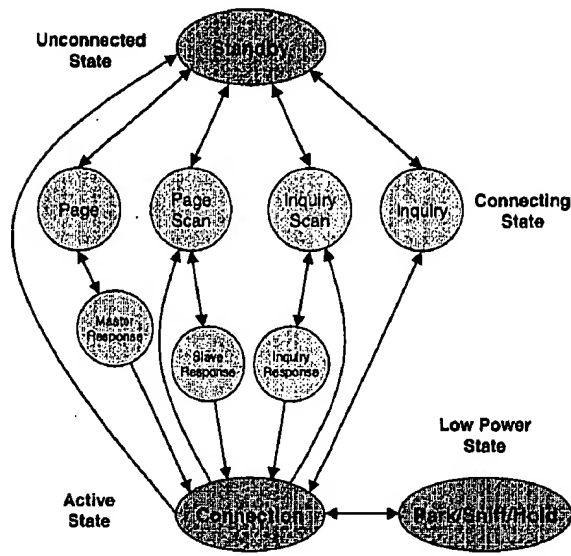


Fig. 2. State diagram of Bluetooth link controller

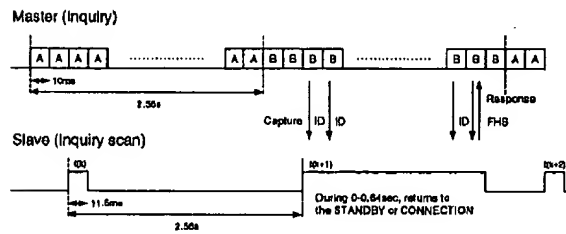


Fig. 3. Inquiry and inquiry scan states in Bluetooth systems [1]

plexity. The Bluetooth radio uses a fast frequency hopping scheme and short data packets to make the link robust in a noisy radio environment. In addition, the use of forward error correction (FEC) limits the impact of random noise. The physical communication range will be in the interval 10 cm to 10 m, but can be extended to above 100 m, which is controlled by the transceiver power in the range -30 dBm to 20 dBm with a nominal value of 0 dBm.

The Bluetooth baseband protocol is a combination of circuit switching and packet switching, where time slots can be reserved for packets carrying synchronous information (synchronous connection oriented voice link) or dynamically allocated for asynchronous information (asynchronous connectionless data link).

### 2.2 Connection procedure of Bluetooth units

In the ad-hoc network, several mobile nodes (e.g., notebook computer, printer, mobile phone, and headset) may get together in a small area and establish peer-to-peer communica-

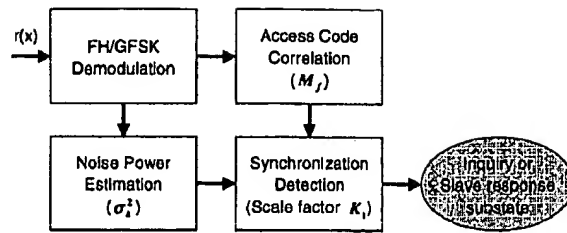


Fig. 4. An adaptive synchronization receiver in the initial state

tion among themselves without the help of any infrastructure such as a wired/wireless backbone. When first establishing a network or adding components to a piconet, the units must be identified. Units can be dynamically connected and disconnected from the piconet at any time [5].

The connect procedure is initiated by one of the unit, the master, which should know the address and clock register value of the other units for the connection. A connection is made either by a page message if the address is already known and clock register value is unknown, or by the inquiry message followed by a subsequent page message if both of the address and clock register value are unknown. When a node receives a packet, it checks the packet identification, and if it is not the destination, transits the next state. Fig. 2 describes a state diagram illustrating the states used in the Bluetooth link controller. As shown in Fig. 2, there are two major states: standby and connection; in addition, there are seven substates denoted as page, page scan, inquiry, inquiry scan, master response, slave response, and inquiry response. In the connection state, the Bluetooth units can be several low-power modes; active mode, sniff mode, hold mode, and park mode. The functional description of inquiry and inquiry scan procedures is summarized in Fig. 3. The page and page scan substates are similar to the inquiry and inquiry scan procedures, respectively [1]. In this paper, the inquiry and inquiry scan states are denoted as the initial state.

## 3. ADAPTIVE TIMING SYNCHRONIZATION SCHEMES IN BLUETOOTH SYSTEMS

### 3.1 Adaptive timing synchronization in the initial state

A block diagram of the FH/GFSK receiver with an adaptive synchronization is shown in Fig. 4. The receiver consists of two channels; one tuned to baseband frequency  $f_1$  corresponding to "space" and the other to frequency  $f_2$  corresponding to "mark". After down-converting and dehopping by the frequency synthesizer, the dehopped signal is then to be processed by the square-law combining FSK receiver [3]. The detector outputs are sampled once every bit duration and the difference between the outputs of two channels is cor-

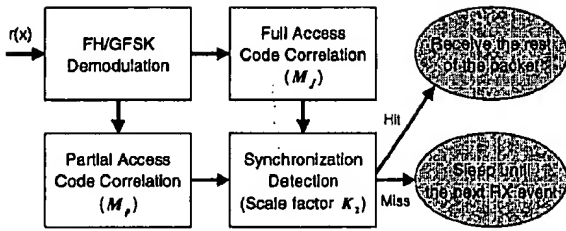


Fig. 5. An adaptive synchronization receiver in the connection state

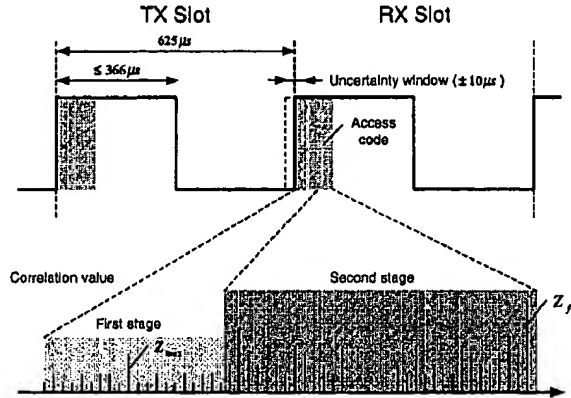


Fig. 6. An example of the correlation outputs in normal mode of the connection state with no timing slipping

related with the inquiry access code (IAC) or device access code (DAC) to produce correlation output  $Z_f$ . The estimated noise variance is multiplied by weighting factor  $K_1$  to produce a synchronization threshold  $\sigma_k^2 K_1$ . If the correlation output exceeds  $\sigma_k^2 K_1$ , the Bluetooth unit will transit inquiry response state, responding a frequency hop synchronization (FHS) packet, when it is in the inquiry scan state and enter slave response substate, replying DAC, when in the page scan state [1].

In practice, the measurement of noise power cannot be accomplished perfectly. As described in [4], however, using reciprocal of the sum of the outputs of the two quadratic detectors achieves the same noise-limited improvement effect as the above mentioned receiver whose performance is based on the perfect estimation of noise power. For analysis purposes, therefore, we have assumed that the measurement of noise variance produces  $\sigma_k^2$  exactly and the pulse response of a Gaussian LPF is rectangular.

### 3.2 Adaptive timing synchronization in the connection state

In the connection state, the connection has been established and packets can be sent back and forth. In both master and slave units, the channel access code and the master Bluetooth

clock are used. During the beginning of the RX cycle, as shown in Fig. 5, the pre-sliding access correlator with length of  $M_p < M_f$  searches for the correct access code over the uncertainty region with length of  $20 \mu s$ . After  $(20 + M_p) \mu s$ , therefore,  $N_w = 20$  partial correlation values are collected and the largest of the resulting  $N_w$  outputs of a pre-sliding correlator,  $Z_{max}$ , is chosen, which is multiplied by scale factor  $K_2$ . The corresponding phase of the largest value is assumed, tentatively, to be coarsely aligned with the received access code signal. After correlating with the remaining  $(M_f - M_p)$ -bit access code, finally, the full correlation value for access code is produced and compared with  $K_2 Z_{max}$ . If a trigger event does occur, the receiver remains open to receive the rest of the packet, which happens with probability  $P_D$  if it is actually the correct phase; otherwise, the receiver goes to sleep until the next RX event. Fig. 6 gives an example for the operation of access code searcher in the case of no timing slipping.

## 4. DETECTION PERFORMANCE OF THE SYNCHRONIZATION RECEIVER

In deriving the probability expressions, we assume that the correlation of the specular sequence and the local access code is negligibly small and can be ignored when they are out of phase ( $H_0$  samples).

### 4.1 Detection probability in the initial state

The region of time/frequency uncertainty of the transmitted phase is divided into samples with one of them denoting the sync-sample (Hypothesis  $H_1$ ) and the others the nonsync-samples (Hypothesis  $H_0$ ). According to the transmitted signal ("space" and "mark"), the sampled detector output of each channel can be represented as

$$r_k^{(s/m)} = \begin{cases} \left( \Lambda_{\cos}^{(s/m), 1k} \right)^2 + \left( \Lambda_{\sin}^{(s/m), 2k} \right)^2, & \text{if energy detected} \\ n_{3k}^{(s/m)^2} + n_{4k}^{(s/m)^2}, & \text{if energy not detected} \end{cases} \quad (1)$$

where  $\Lambda_{\cos/\sin}^{(s/m), ik} = \sqrt{2P} \cos/\sin \theta_k^{(s/m)} + n_{ik}^{(s/m)}$ ,  $P$  is the signal power,  $\{\theta_k^{(s/m)}\}$  are the uniform phase random variable,  $\{n_{ik}^{(s/m)}\}$  are the independent zero-mean Gaussian with variance  $\sigma_k^2$  in each channel, and  $(s/m)$  notation denotes the corresponding term-wise pair.

Under the assumption of the same average noise power in both "mark" and "space" channels, after correlating the difference between the outputs of two channels with IAC or DAC, the output of the correlator of  $H_1$  sample is expressed

as

$$Z_f = \frac{1}{M_f} \left\{ \sum_{k=1}^{M_f^{+1}} \sigma_k^2 \left[ \left( \Omega_{\cos}^{(s), 1k} \right)^2 + \left( \Omega_{\sin}^{(s), 2k} \right)^2 - \omega_k^{(s)2} \right] + \sum_{k=1}^{M_f^{-1}} \sigma_k^2 \left[ \left( \Omega_{\cos}^{(m), 1k} \right)^2 + \left( \Omega_{\sin}^{(m), 2k} \right)^2 - \omega_k^{(m)2} \right] \right\} \quad (2)$$

where  $\Omega_{\cos/\sin}^{(x), ik} = \sqrt{\frac{2P}{\sigma_k^2}} \cos/\sin \theta_k^{(x)} + w_{ik}^{(x)}$ ,  $\omega_k^{(x)2} = w_{3k}^{(x)2} + w_{4k}^{(x)2}$ ,  $M_f = M_f^{+1} + M_f^{-1}$ ,  $\{w_{ik}^{(s/m)}\}$  are independent Gaussian random variables with zero mean and unit variance, and the received noise power of each channel is  $\sigma_k^2 = N_0 B$  with probability  $1 - r$  and  $\sigma_k^2 = (N_0 + N_J/r)B$  with probability  $r$ , respectively.  $M_f^{+1}$  is the number of one's in the access code,  $M_f^{-1}$  is the number of zero's in the access code,  $B$  is the cell bandwidth, and  $N_0$  and  $N_J$  are the thermal noise spectral density and the average jamming noise spectral density, respectively.

To evaluate the probability distribution function (PDF) of correlation output, based on the central limit theorem, we have assumed that the correlation term is Gaussian [6]. Fortunately, since a 64-bit synchronization word is used in the Bluetooth system (i.e.,  $M_f = 64$ ); such an approximation is certainly feasible. From the above discussions, the PDF of  $Z_f$  under hypothesis  $H_1$ ,  $p_f(z|H_1)$ , follows the Gaussian distribution with mean  $m_f = 2P$  and variance  $\sigma_f^2 = 8(\sigma_k^2 P + \sigma_k^4)/M_f$ .

Under the assumption that the noise power is estimated exactly, the detection probability,  $P_D$ , is the probability that the  $H_1$  sample exceeds the threshold  $\sigma_k^2 K_1$ , which can be evaluated as

$$P_D = (1 - r)Q\left(\frac{K_1 - 2\rho_1}{\zeta_1}\right) + rQ\left(\frac{K_1 - 2\rho_2}{\zeta_2}\right) \quad (3)$$

where  $\rho_1 = E_b/N_0$ ,  $\rho_2 = E_b/(N_0 + N_J/r)$ ,  $\zeta_i = \sqrt{8(\rho_i + 1)/M_f}$ , and  $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$ .

#### 4.2 Detection probability in the connection state

In a first stage, the partial correlation output  $Z_p$  under hypothesis  $H_1$  can be expressed in an identical form to eqn. (2) with  $M_f^{+1}$  and  $M_f^{-1}$  replaced by  $M_p^{+1}$  and  $M_p^{-1}$  ( $M_p = M_p^{+1} + M_p^{-1}$ ), respectively. From the above discussion, the PDF of  $Z_p$  under  $H_1$ ,  $p_p(z|H_1)$ , follows the Gaussian distribution with mean  $m_p = 2PM_p/M_f$  and variance  $\sigma_p^2 = 8M_p(\sigma_k^2 P + \sigma_k^4)/M_f^2$ , while the PDF of  $Z_p$  under  $H_0$  denoted by  $p_p(z|H_0)$  follows the zero mean Gaussian distribution with variance  $\sigma_p^2$ . Then, the PDF of  $K_2 Z_{max}$  under

hypothesis  $H_1$  can be expressed as

$$p_{max}(z|H_1) = \frac{d}{dz} \left[ \left\{ 1 - Q\left(\frac{z - K_2 m_p}{\sqrt{2} K_2 \sigma_p}\right) \right\}^{N_w} \right] \quad (4)$$

and the PDF of  $K_2 Z_{max}$  under  $H_0$  is given by

$$p_{max}(z|H_0) = \frac{d}{dz} \left[ \left\{ 1 - Q\left(\frac{z}{\sqrt{2} K_2 \sigma_p}\right) \right\}^{N_w-1} \cdot \left\{ 1 - Q\left(\frac{z + K_2 m_p}{\sqrt{2} K_2 \sigma_p}\right) \right\} \right] \quad (5)$$

In a second stage, correlating with the remaining  $(M_f - M_p)$ -bit access code produces the full correlation value of the access code with length  $M_f$ , which is expressed in the same form as eqn. (2). Then, the conditional probability of a successful detection is the probability that the full correlation value exceeds  $K_2 Z_{max}$ , which is given by

$$P_{DS}^i = \int_{-\infty}^{\infty} p_f(x|H_1) \int_{-\infty}^x p_{max}(y|H_1) dy dx \quad (6)$$

while, when a false detection occurs, the conditional probability of a false detection is given by

$$P_{DF}^i = \int_{-\infty}^{\infty} p_f(x|H_0) \int_{-\infty}^x p_{max}(y|H_0) dy dx \quad (7)$$

which can be further derived as

$$P_{DS}^i = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\zeta_i} e^{-\frac{(x-2\rho_i)^2}{2\zeta_i^2}} \cdot \left\{ 1 - Q\left(\frac{x - 2\lambda^2 \rho_i}{\sqrt{2} K_2 \lambda \zeta_i}\right) \right\}^{N_w} dx \quad (8)$$

and

$$P_{DF}^i = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\zeta_i} e^{-\frac{x^2}{2\zeta_i^2}} \left\{ 1 - Q\left(\frac{x + 2\lambda^2 \rho_i}{\sqrt{2} K_2 \lambda \zeta_i}\right) \right\} \cdot \left\{ 1 - Q\left(\frac{x}{\sqrt{2} K_2 \lambda \zeta_i}\right) \right\}^{N_w-1} dx \quad (9)$$

where  $\lambda = \sqrt{K_2 M_p / M_f}$ .

Finally, the total probabilities of a successful detection and a false detection can be obtained as follows  $P_D = (1 - r)P_{DS}^1 + rP_{DS}^2$  and  $P_{FA} = (1 - r)P_{DF}^1 + rP_{DF}^2$ , respectively.

## 5. NUMERICAL RESULTS AND DISCUSSIONS

Numerical behaviors of the proposed synchronization scheme in the Bluetooth network are presented in this section. Throughout this section the parameters  $M_f = 64$ ,  $N_w = 20$ , and  $B = 1$  MHz are assumed. The values of weighting factors  $K_1$  and  $K_2$  are chosen to ensure  $P_{FA}$  an acceptable rate for each value of  $E_b/N_0$  and  $E_b/N_J$ .

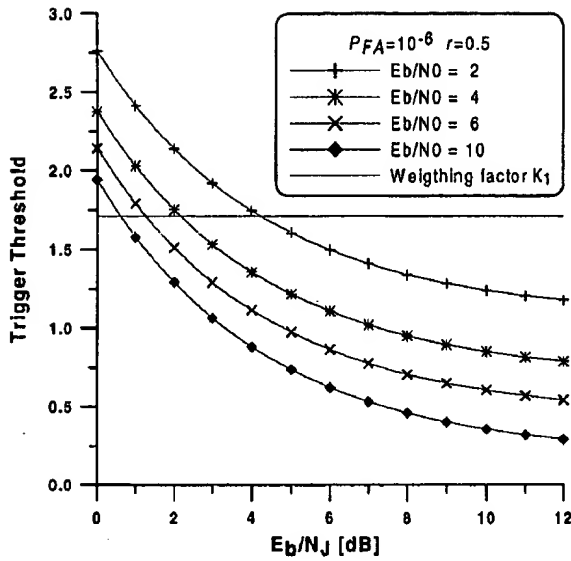


Fig. 7. Trigger threshold versus  $E_b/N_J$  for various values of  $E_b/N_0$  ( $P_{FA} = 10^{-6}$  and  $r = 0.5$ )

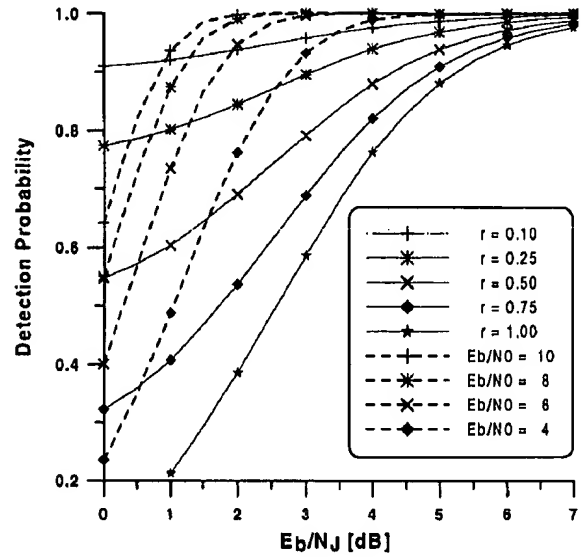


Fig. 8. Performance of the synchronization receiver for various values of  $r$  and  $E_b/N_0$  with  $P_{FA} = 10^{-6}$ : (1) solid line -  $E_b/N_0 = 2$  [dB] and (2) dashed line -  $r = 1.0$

### 5.1 Numerical behavior in the initial state

Figs. 7 ~ 8 present the performance of the timing synchronization receiver in the initial state for various system and channel parameters under the partial-band noise environments. Though the master does not broadcast message, the correlation output of slave's unit may exceed the threshold  $\sigma_k^2 K_1$  due to the noise interferences during the initial state. Under hypothesis  $H_0$ , this happens with probability  $P_{FA} = (1 - r)Q(K_1/\zeta_1) + rQ(K_1/\zeta_2)$ .

Fig. 7 presents the actual trigger threshold versus  $E_b/N_J$  with  $r = 0.5$  and  $P_{FA} = 10^{-6}$ . The solid line represents the values of  $K_1$  for various values of  $E_b/N_0$  and  $E_b/N_J$ . It is clear from Fig. 7 that values of the weighting factor  $K_1$  is insensitive to the partial-band noise interferences and an adaptive setting of the actual trigger threshold can be obtained by setting the weighting factor to a fixed value.

Performance of the synchronization receiver for various values of partial-band jamming fractions  $r$  and  $E_b/N_0$  with  $P_{FA} = 10^{-6}$  is shown in Fig. 8. As expected, for lower  $E_b/N_J$ , a severe degradation in the detection probability due to the partial-band jamming noise is observed. For a partial-band jamming fraction of  $r = 1$ , however, the performance degradation according to the variation of  $E_b/N_0$  is negligible, which is thanks to the deemphasis of jammed hops provided by the nonlinear combining scheme. The output of correlation detector when a hop contains a large amount of interference will be smaller than the output when interfer-

ence is not present, and the hops without interference will have a greater influence on the detection performance.

### 5.2 Numerical behavior in the connection state

The performance of the timing synchronization receiver in the connection state for various system and channel parameters is examined under the partial-band noise environments in Figs. 9 ~ 12.

Fig. 9 illustrates the sensitivity of the detection probability with respect to the scale factor  $K_2$  and  $M_p$  for a fixed value of  $E_b/N_0 = E_b/N_J = 6$  [dB] and  $r = 0.25$ . It is shown in Fig. 9 that the product value of  $K_2$  and  $M_p$  to give  $P_D > 0.9$  is about less than 50. In the case of Fig. 9, therefore, the synchronization detection can be appropriate as long as the parameters  $K_2$  and  $M_p$  are selected to satisfy the condition  $K_2 M_p < 50$ . Also, a severe degradation in the detection probability due to the improper setting of system parameters can be observed.

Performance of the synchronization receiver for partial-band jamming fractions  $r$  with  $P_{FA} = 10^{-6}$ ,  $M_p = 30$ , and  $E_b/N_0 = 6$  [dB] is depicted in Fig. 10. It is observed from Fig. 10 that the variation of the detection probability is insignificant as compared with that of detection probability in Fig. 8. This is due to the fact that the RX timing is based on the latest successful trigger during a master-to-slave slot in the connection state, i.e., the Bluetooth unit has the addresses and clocks of units in range.

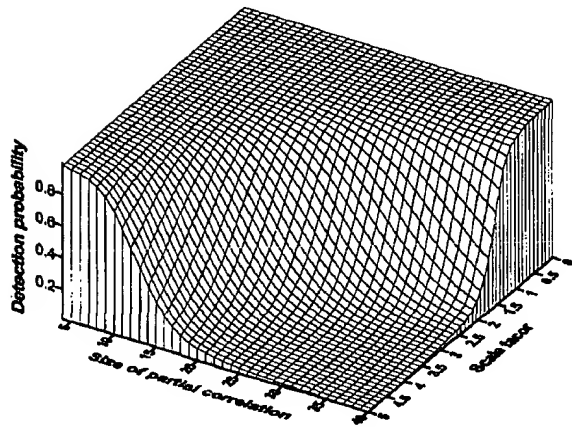


Fig. 9. Sensitivity of the detection probability with respect to various values of  $K_2$  and  $M_p$  with  $E_b/N_0 = E_b/N_J = 6$  [dB] and  $r = 0.25$

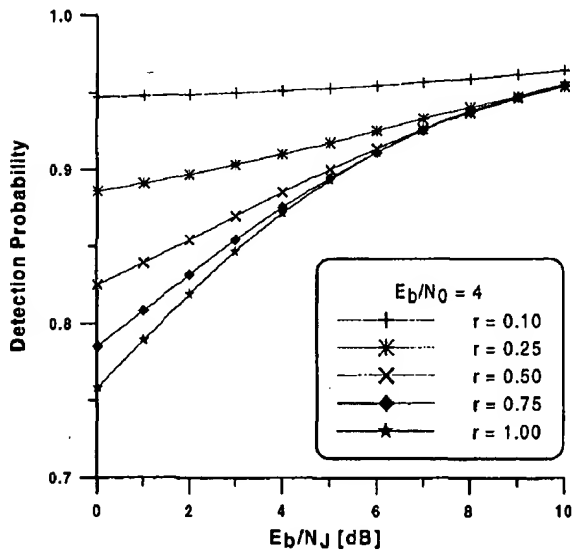


Fig. 10. Performance of the synchronization receiver for partial-band jamming fractions of  $r = 0.1, 0.25, 0.5, 0.75$ , and  $1.0$  ( $P_{FA} = 10^{-6}$ ,  $M_p = 30$ , and  $E_b/N_0 = 6$  [dB])

Fig. 11 presents the detection performance of the synchronization receiver for various values of  $E_b/N_0$  and  $E_b/N_J$  with  $P_{FA} = 10^{-6}$ ,  $M_p = 30$ , and  $r = 1.0$ . It is shown from Fig. 11 that the detection probability is less sensitive to the variation of  $E_b/N_J$  and the thermal noise is a dominating term compared with the jamming noise.

Fig. 12 shows the influence of the partial-band jamming noise on the detection probability for various values of  $E_b/N_0$  with  $P_{FA} = 10^{-6}$  and  $M_p = 30$ . For higher  $E_b/N_J$ ,

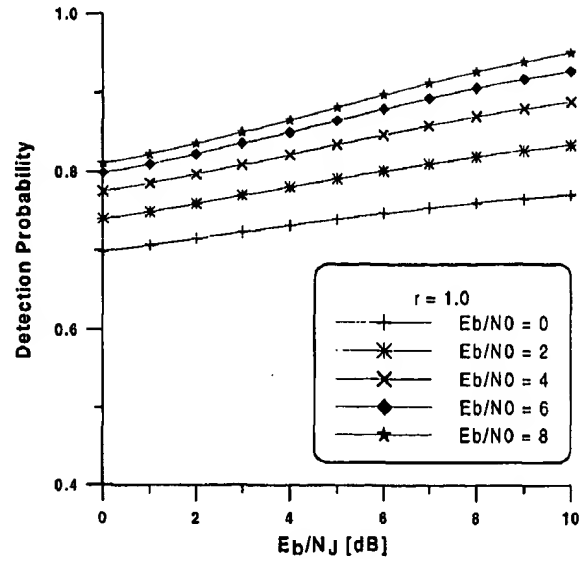


Fig. 11. Performance of the synchronization receiver for various values of  $E_b/N_0$  ( $P_{FA} = 10^{-6}$ ,  $M_p = 30$ , and  $r = 1.0$ )

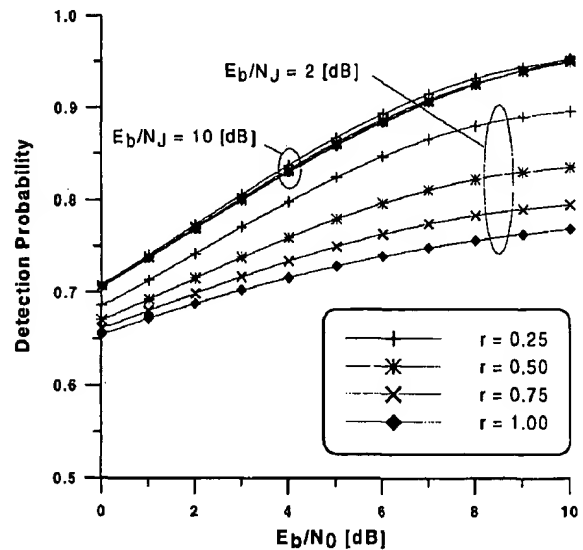


Fig. 12. Performance of the synchronization receiver for partial-band jamming fractions of  $r = 0.25, 0.5, 0.75$ , and  $1.0$  with  $E_b/N_J = 2$  and  $10$  [dB] ( $P_{FA} = 10^{-6}$  and  $M_p = 30$ )

the degradation of the detection performance due to the unwanted partial-band jamming noise is negligible. On the other hand, for lower  $E_b/N_J$ , the detection probability of the synchronization receiver depends heavily on the partial-band jamming noise.

## 6. CONCLUSIONS

The detection performance of the proposed synchronization receivers for a short-ranged radio system has been addressed in the partial-band noise environments. Their synchronization performance is robust against the partial-band noise jamming interferences. Especially, these schemes are suitable for the low-cost and low-complexity technologies like Bluetooth, HomeRF, and HomeCast.

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